Results from the MAJORANA DEMONSTRATOR

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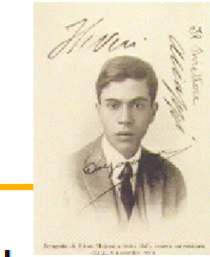
On behalf of the MAJORANA Collaboration

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, the Particle Astrophysics and Nuclear Physics Programs of the National Science Foundation, and the Sanford Underground Research Facility.

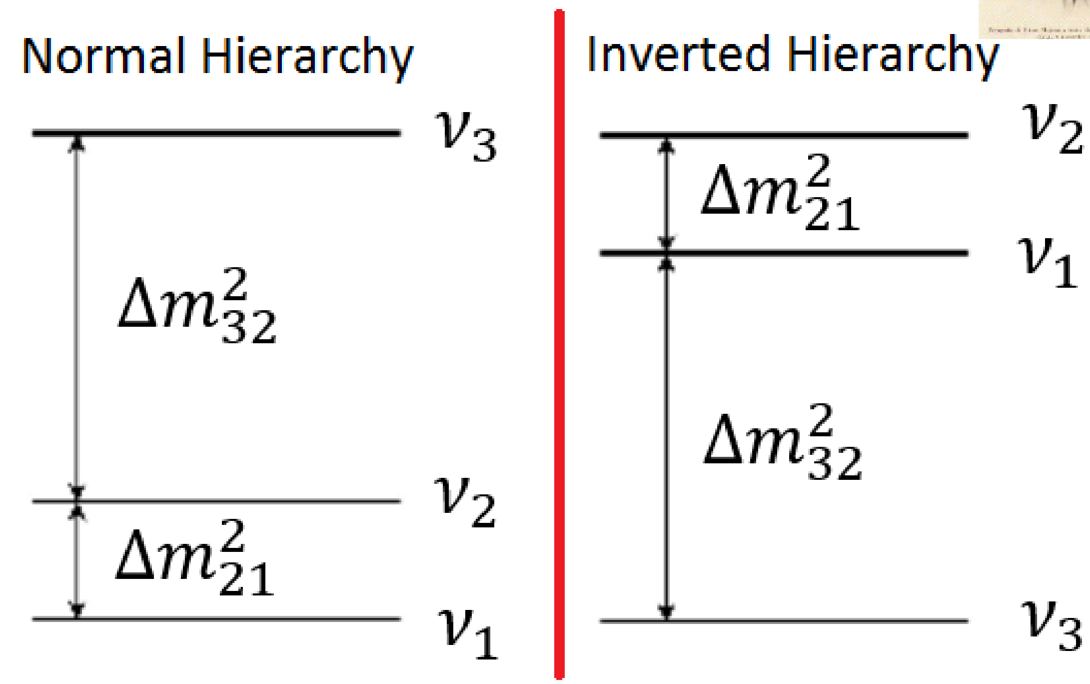
Physics Motivation

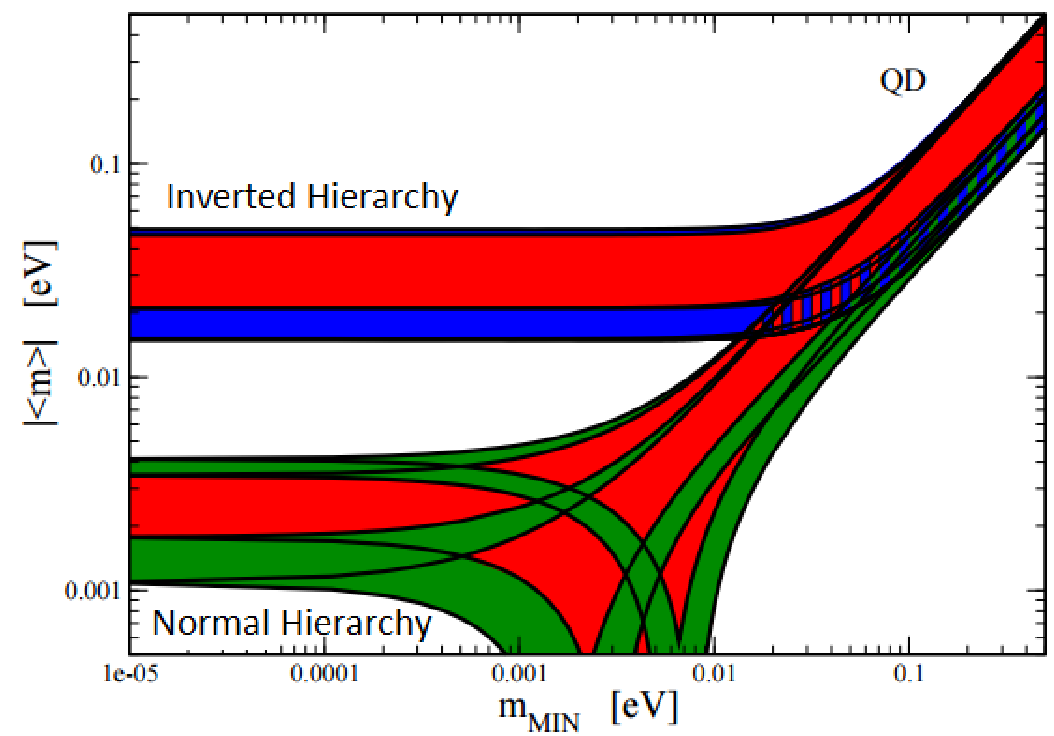


Neutrino Mass Hierarchy Problem:
- Until recently neutrinos were thought to be massless
- The absolute neutrino mass scale is unknown
- Neutrino oscillation experiments can only measure the squared difference of the masses

Neutrinoless-Double Beta Decay:
- Hypothetical process in which only electrons are emitted
- Observable only if neutrinos are Majorana particles

If $0\nu\beta\beta$ decay is observed $\Longrightarrow$
Neutrinos are Majorana particles,
Lepton number is violated,
Sheds light on the absolute neutrino mass scale. ($\Gamma_{0\nu\beta\beta} \propto |m_{eff}|^2$)



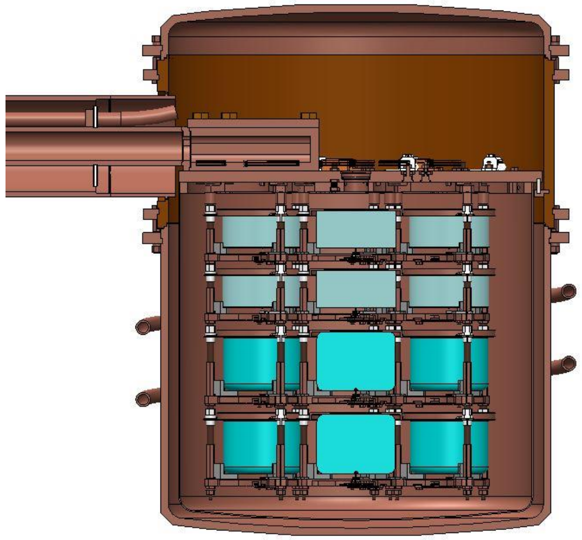


Effective majorana mass as a function of the lightest neutrino mass

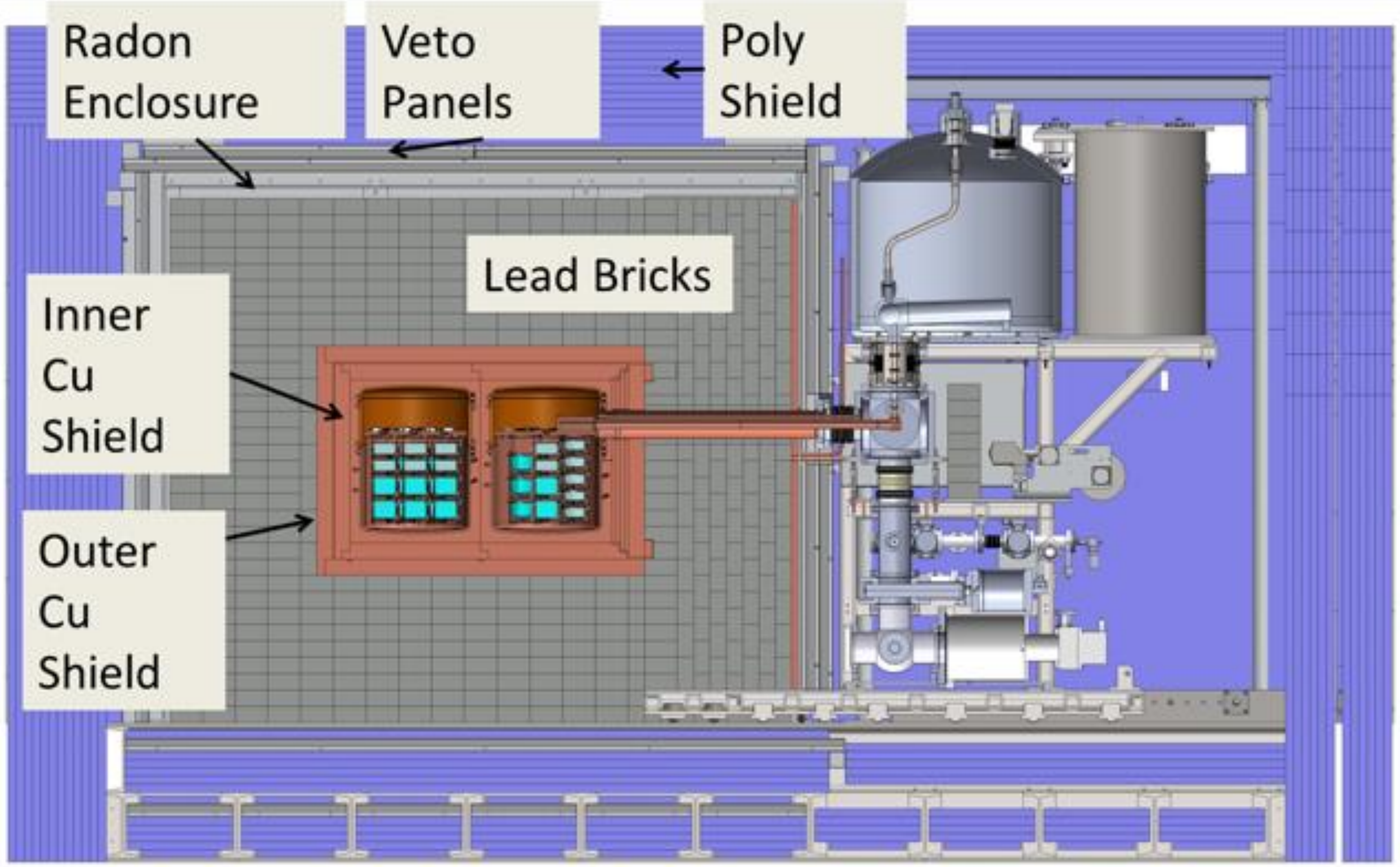
The MAJORANA DEMONSTRATOR

Operating 4850' underground at the Sanford Underground Research Facility, Lead, SD.

Goals:
- Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.



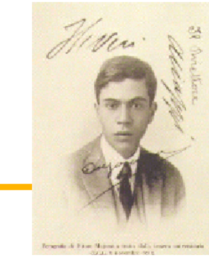
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI-t-y (after analysis cuts); Measured Assay U.L. ≤ 3.5 counts/ROI-t-y
- Energy resolution of 2.4 keV FWHM @ 2039 keV (best of any $0\nu\beta\beta$ experiment)
- 44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals (35 detectors)
  - 14.4 kg of ^{nat}Ge (23 detectors)
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



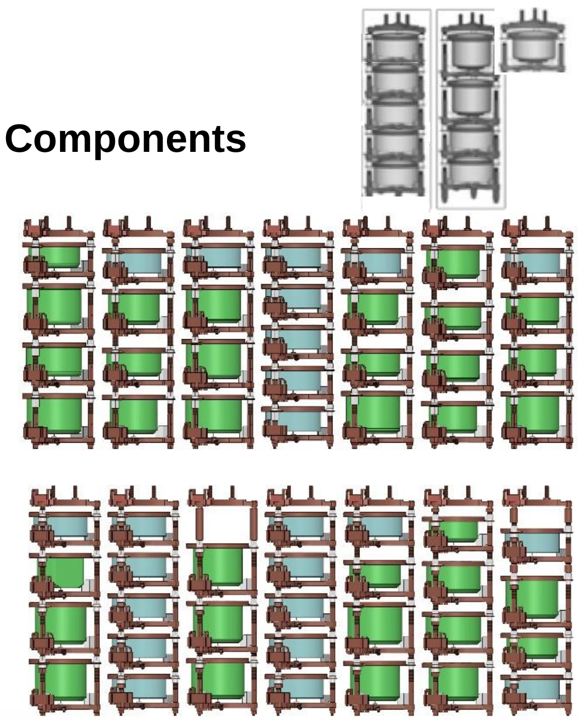
N. Abgrall *et al.*, Adv. High Ener. Phys. **2014**, 365432 (2013)
arXiv:1308.1633

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics with additional contributions from international collaborators.

MAJORANA DEMONSTRATOR Implementation



Three Steps



Prototype cryostat: 7.0 kg (10) ^{nat}Ge

Same design as Modules 1 and 2, but fabricated using OFHC Cu Components

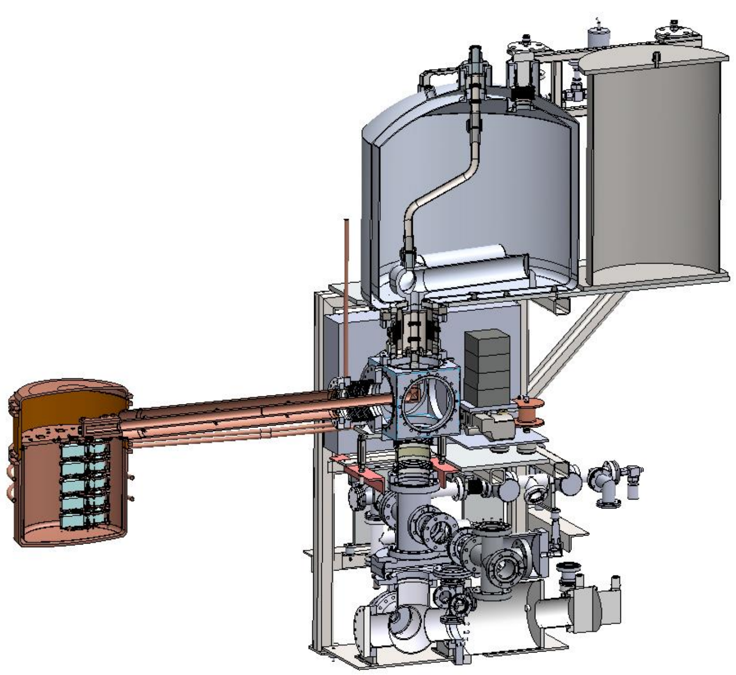
June 2014-June 2015

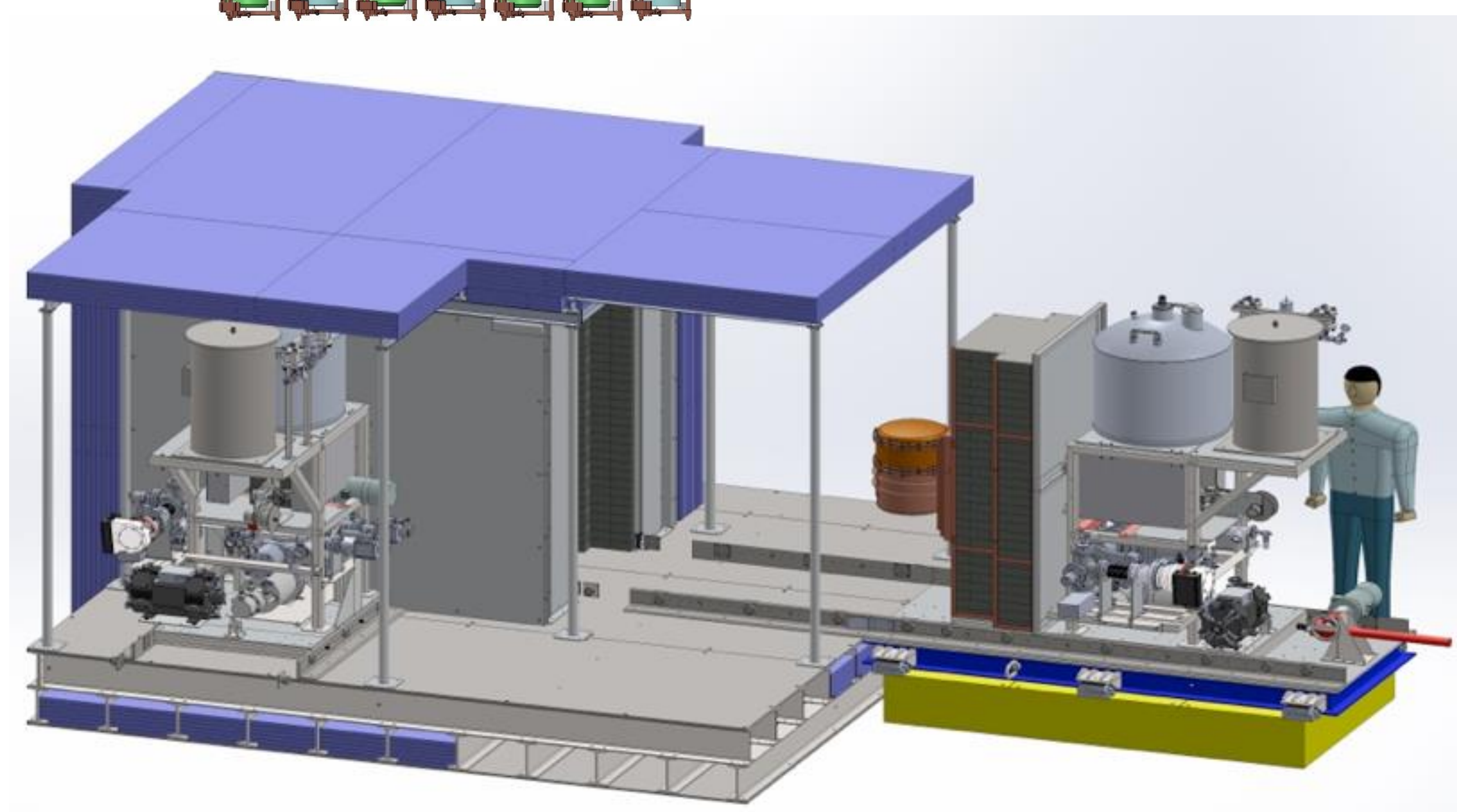
Module 1: 16.9 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge

9/2014: Module commissioning
5/2015 - 10/2015: In-shield running
10/2015 - 1/2016: Offline, upgrades
1/2016 - Present: in-shield running

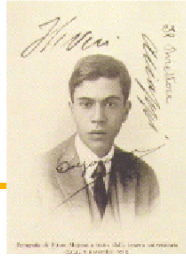
Module 2: 12.9 kg (15) ^{enr}Ge
8.8 kg (14) ^{nat}Ge

4/2016: Module commissioning
7/2016 - Present: In-shield running



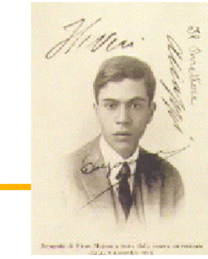


Advantages of ^{76}Ge detectors



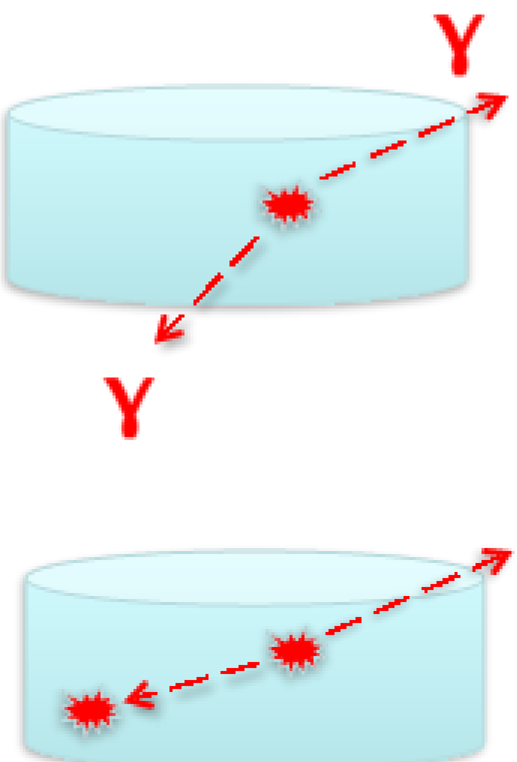
- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution:
  approaching 0.1% at 2039 keV (~3 keV ROI)
- Demonstrated ability to enrich from 7.44% to ≥ 87%
- Powerful background rejection:
  - Granularity: multiple detectors hit
  - Pulse shape discrimination (PSD): multiple hits in a detector
  - Alpha events near surface: based on response

Ge Detector PSD efficiency

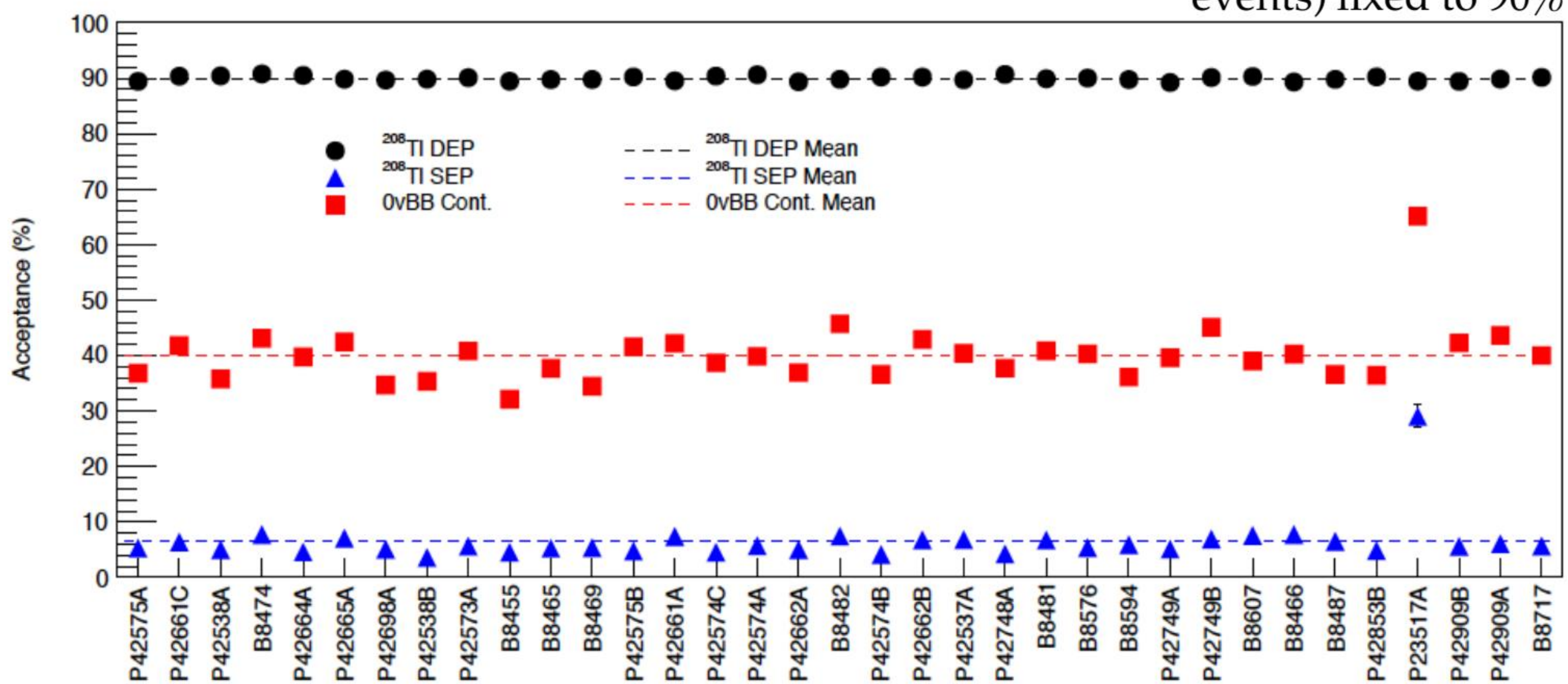


PSD cuts are optimized to keep 90% of single site and < 10% of multi-site events

- $0\nu\beta\beta$ is a singe site event
- ^{208}Tl 2614 keV γ can pair produce and emit 2 γ, used to adjust PSD
- Both γ's escape from detectors → Double escape peak (DEP), single site
- One γ escapes from detectors → Single escape peak (SEP), multi-site

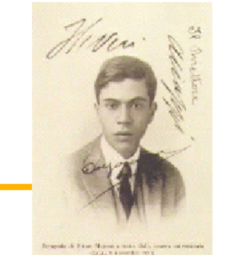


^{208}Tl DEP (single site events) fixed to 90%



^{208}Tl SEP (multiple site events) reduced to 6%

Delayed Charge Recovery and Alphas



Alpha background response observed in Module 1 commissioning (DS0)

- Identified as arising from alpha particles impinging on passivated surface

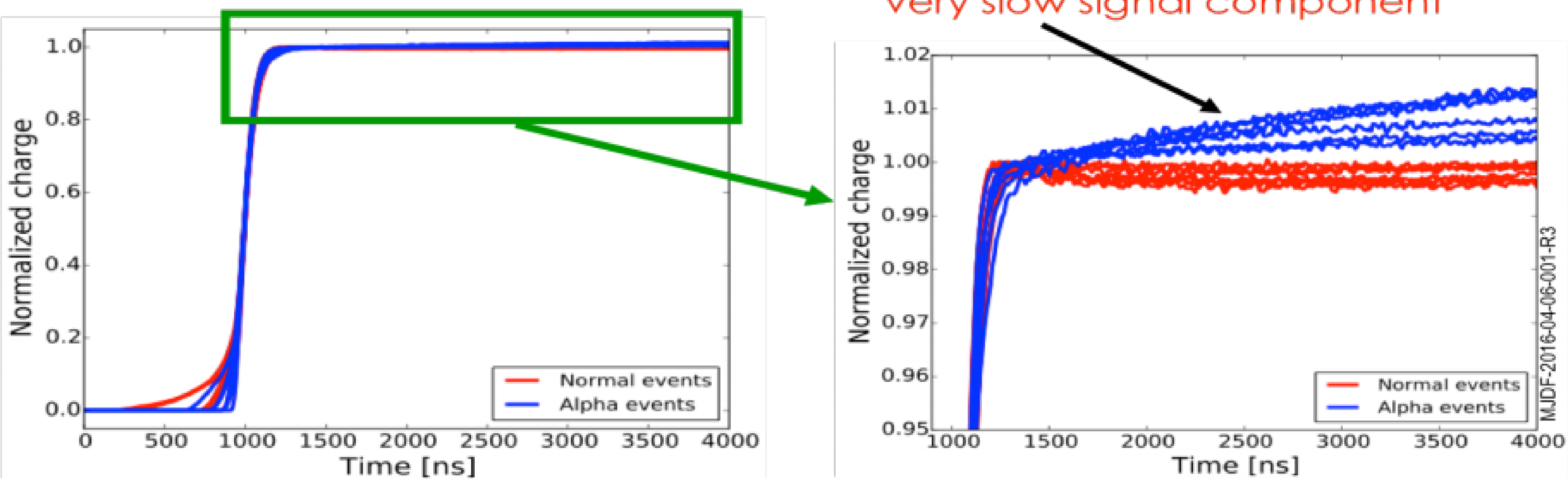
Results in prompt collection of some energy, plus very slow collection of remainder

Produces a distinctive waveform allowing a high efficiency cut

- “Delayed Charge Recovery” (DCR) parameter related to slope of tail

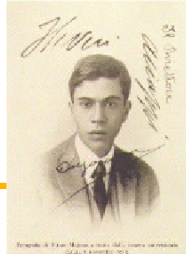
Example pole-zero corrected waveforms

Slow drift of charges along passivated surface results in very slow signal component



DCR paper arXiv:1610.03054

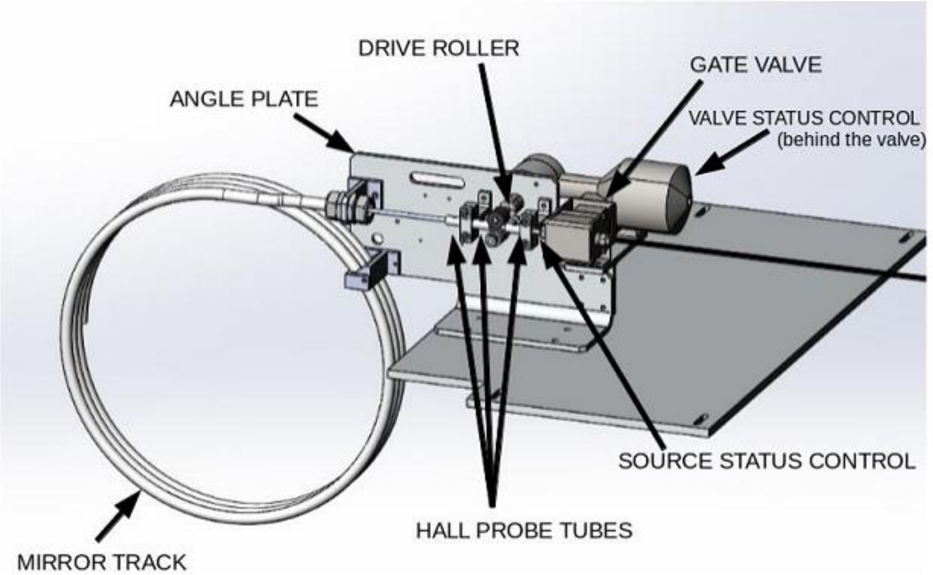
Detector Calibration

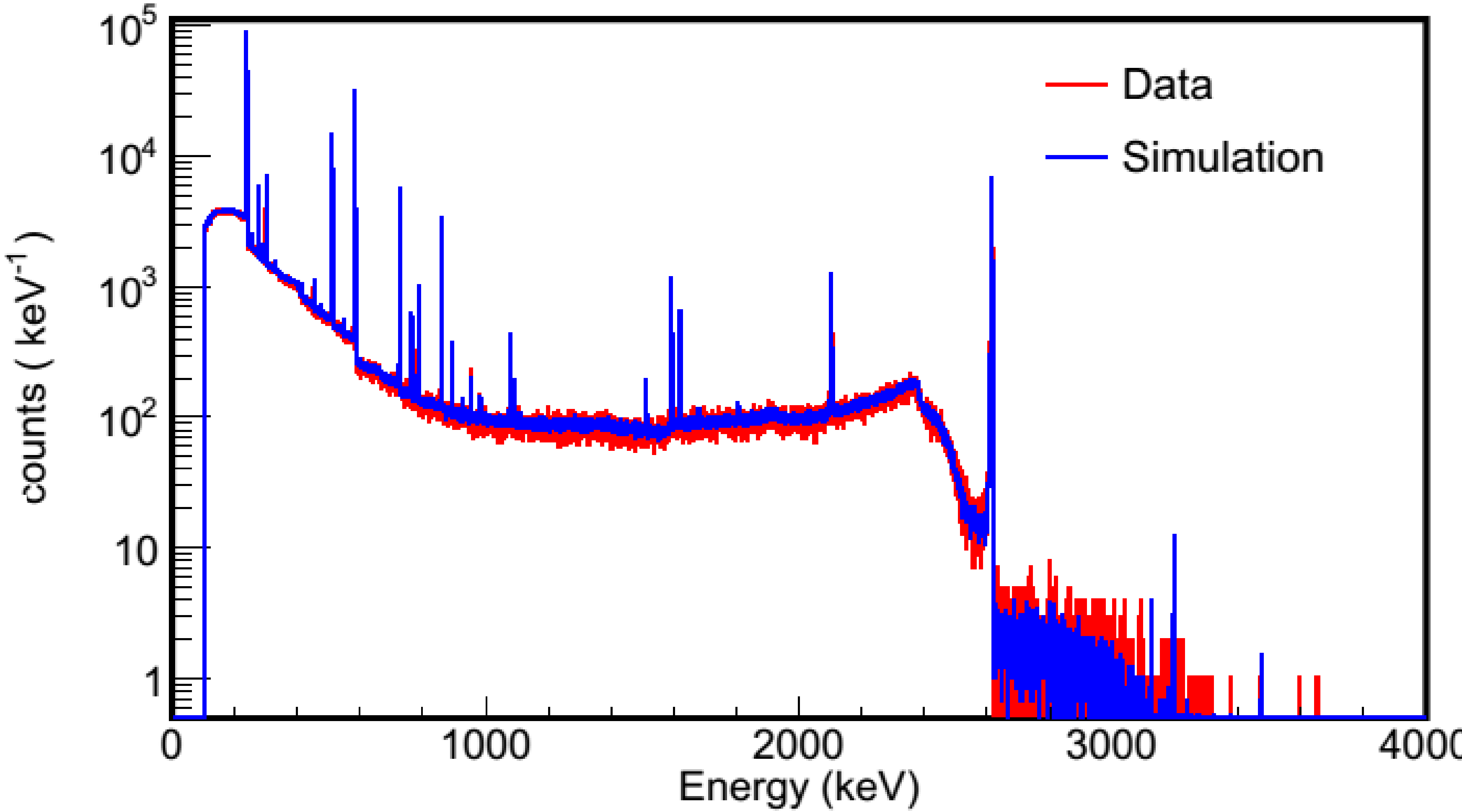


- Modules 1 and 2
- ^{228}Th calibration line source
- FWHM = 2.4keV at $Q_{\beta\beta}$ (2039 keV)

MaGe paper
Boswell et al. IEEE Trans.Nucl.Sci. 58 (2011) [arXiv:1011.3827]

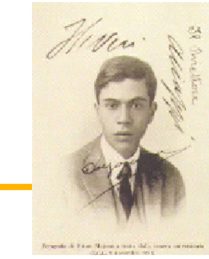
Calibration paper
arXiv:1702.02466





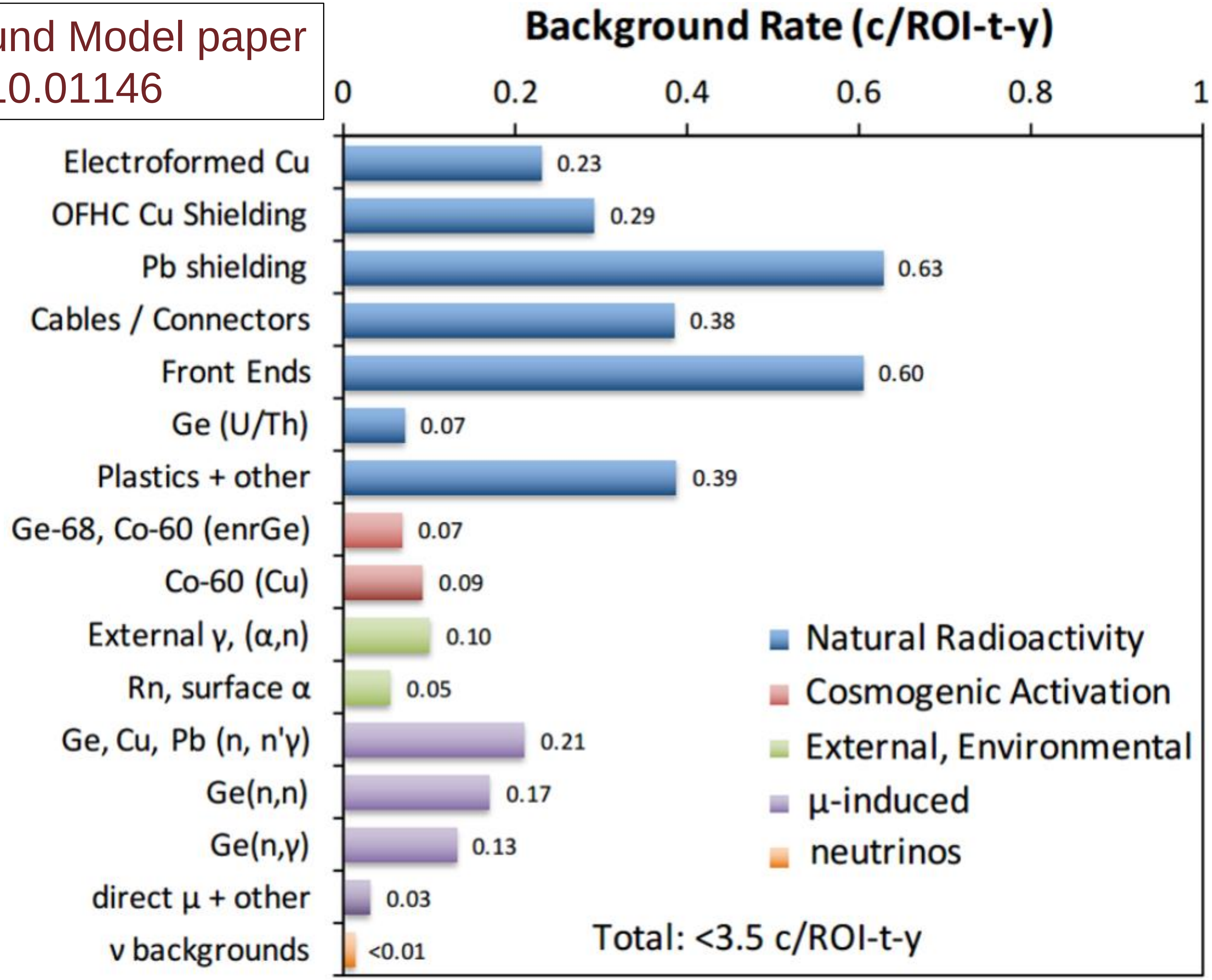
Comparison of a ^{228}Th line source simulation using MaGe and a measurement of M1. The simulated distribution was normalized by matching the integrals of both curves in the range from 2595 keV to 2635 keV.

DEMONSTRATOR Background Model

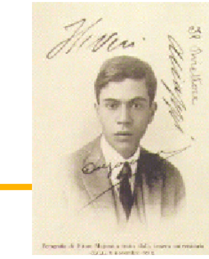


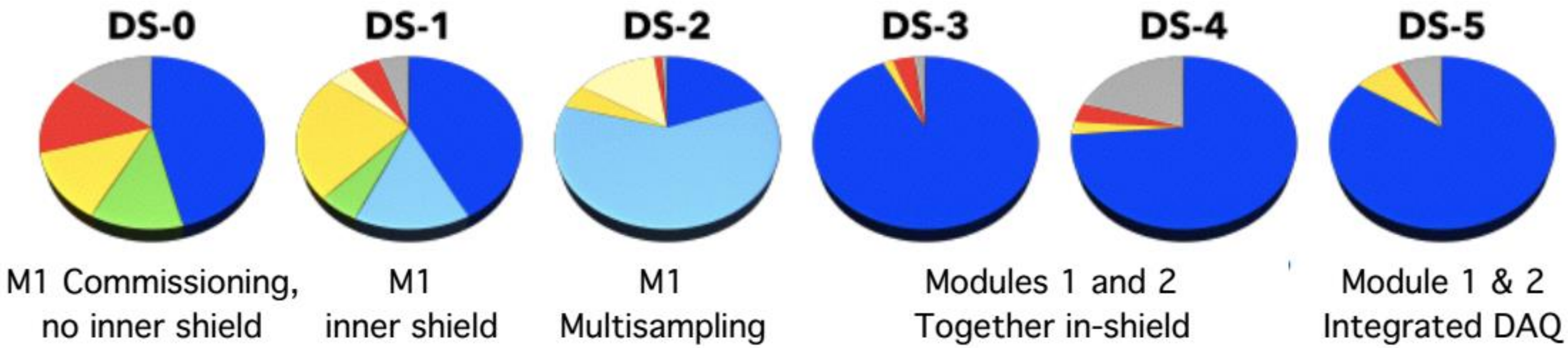
Radioassay paper: NIMA 828 (2016) 22 [arXiv:1601.03779]

Background Model paper
arXiv:1610.01146



Duty Cycles and Livetime





	DS-0 Module 1 June 26 - Oct. 7, 2015	DS-1 Module 1 Dec. 31, 2015 - May 24, 2016	DS-2 Module 1 May 24 - July 14, 2016	DS-3 Module 1 Aug. 25 - Sep. 27, 2016	DS-4 Module 2 Aug. 25 - Sep. 27, 2016	DS-5 Module 1 & 2 Oct. 13, 2016 - ***May. 11 2017******
Total (days)	103.15	144.50	50.97	32.37	32.36	97.7
Total acquired	87.93	136.98	50.47	31.73	25.80	90.41
Physics *	47.70	61.34 + 20.41*	9.82 + 30.56*	29.97	23.84	82.52
High radon	11.76	7.32	-	-	-	-
Calibration	15.44	7.32	0.65	1.18	1.17	1.39
Down time	15.21	7.51	0.50	0.64	6.56	7.29
Disruptive/ Commissioning *	13.10	34.43+ 5.92*	2.41 + 7.03*	0.57	0.78	6.51

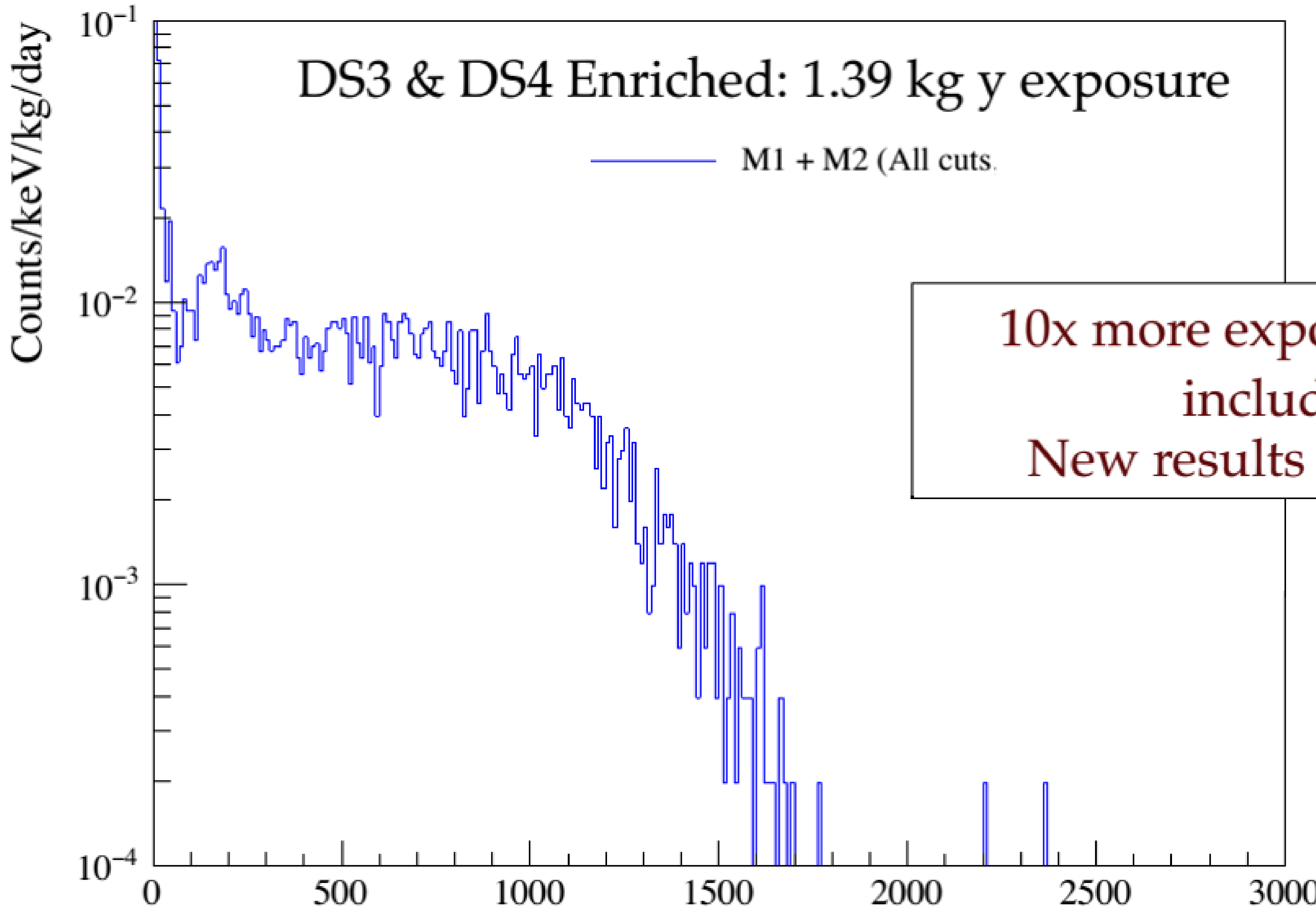
*Blind data

*Values up to Jan. 19, 2017

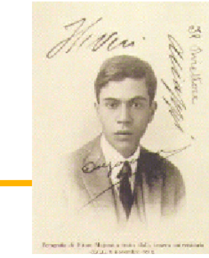
DS6 has started with multisampling and blindness.

$0\nu\beta\beta$ Region of Interest (DS-3 & DS-4)

- After cuts, 1 count in 400 keV window centered at 2039 keV ($0\nu\beta\beta$ peak)
  - Background index of 1.8 x 10^{-3} c/(keV kg y)
  - Projected background rate is $5.1^{+8.9}_{-3.2}$ c/(ROI t y) for a 2.9 keV (M1/DS3) & 2.6 keV (M2/DS4) keV ROI, (68%CL).
- Analysis cuts are still being optimized.

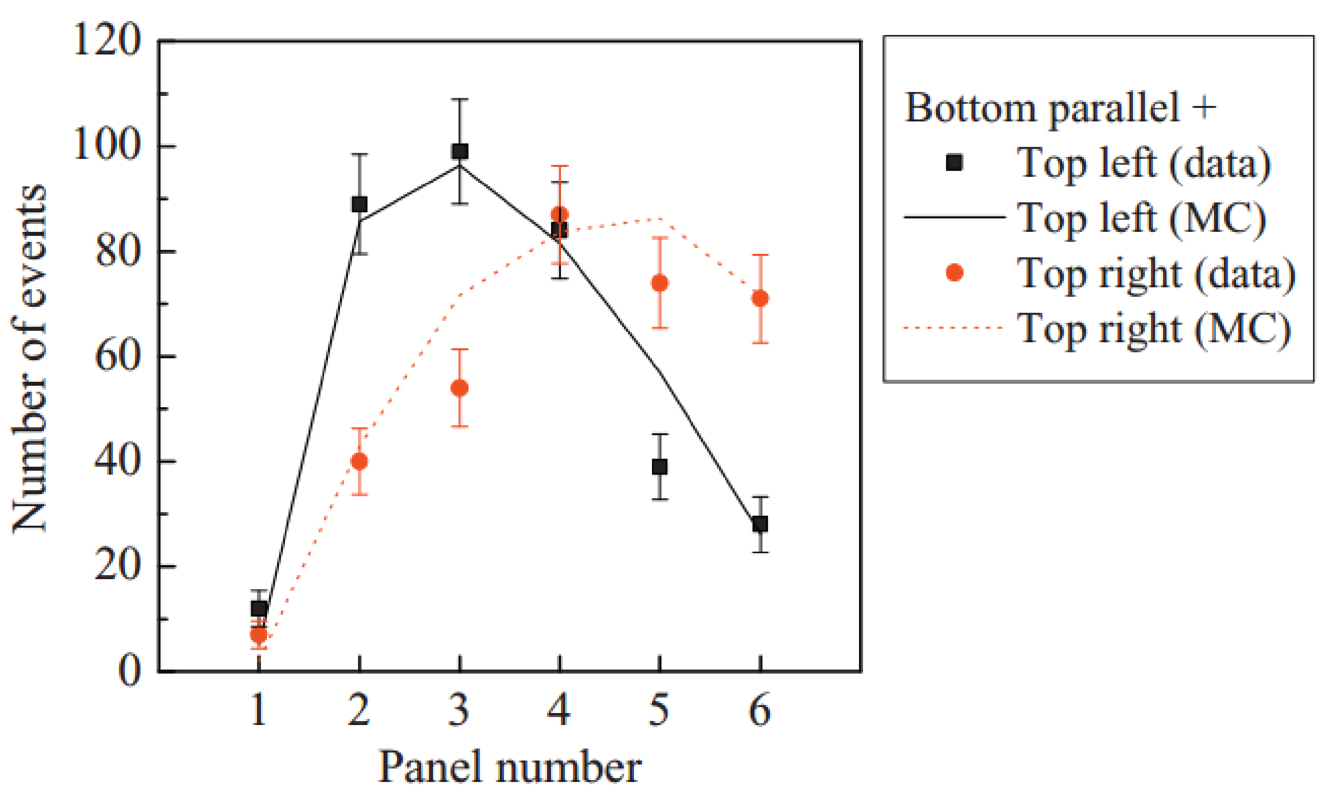


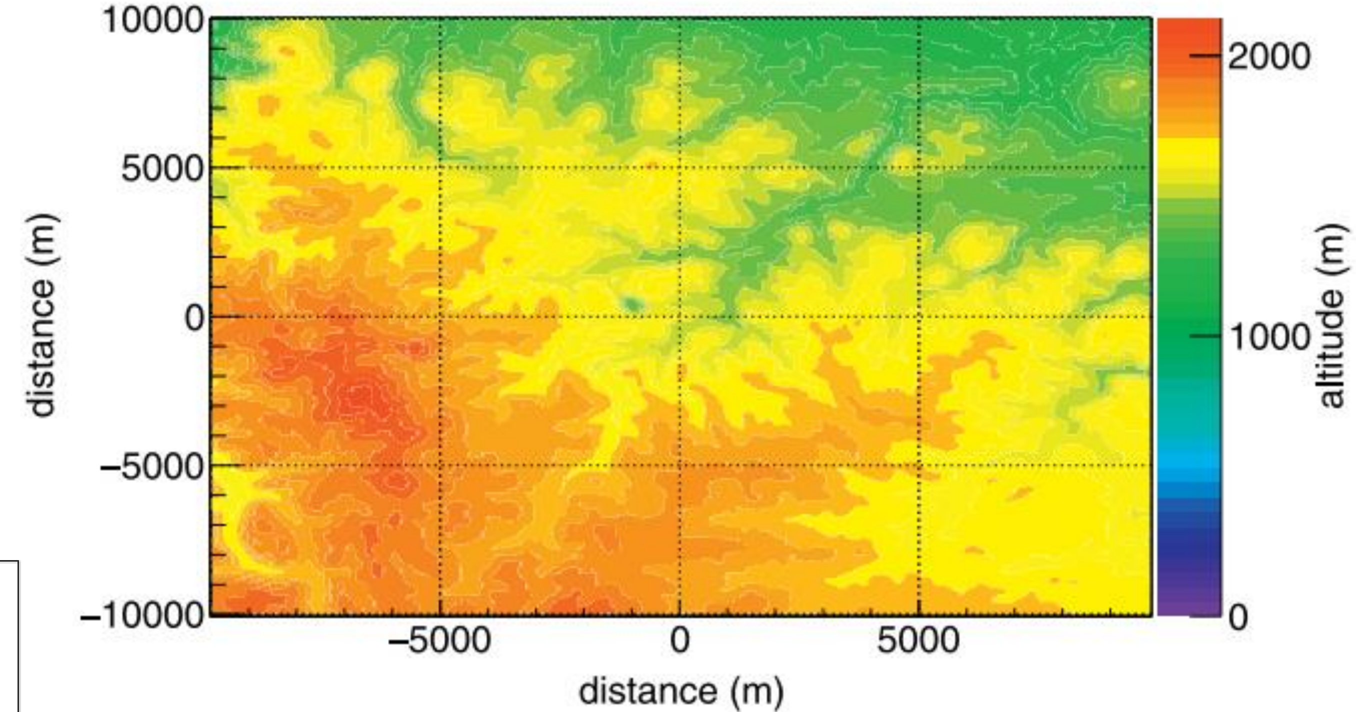
Muon Flux Measurement

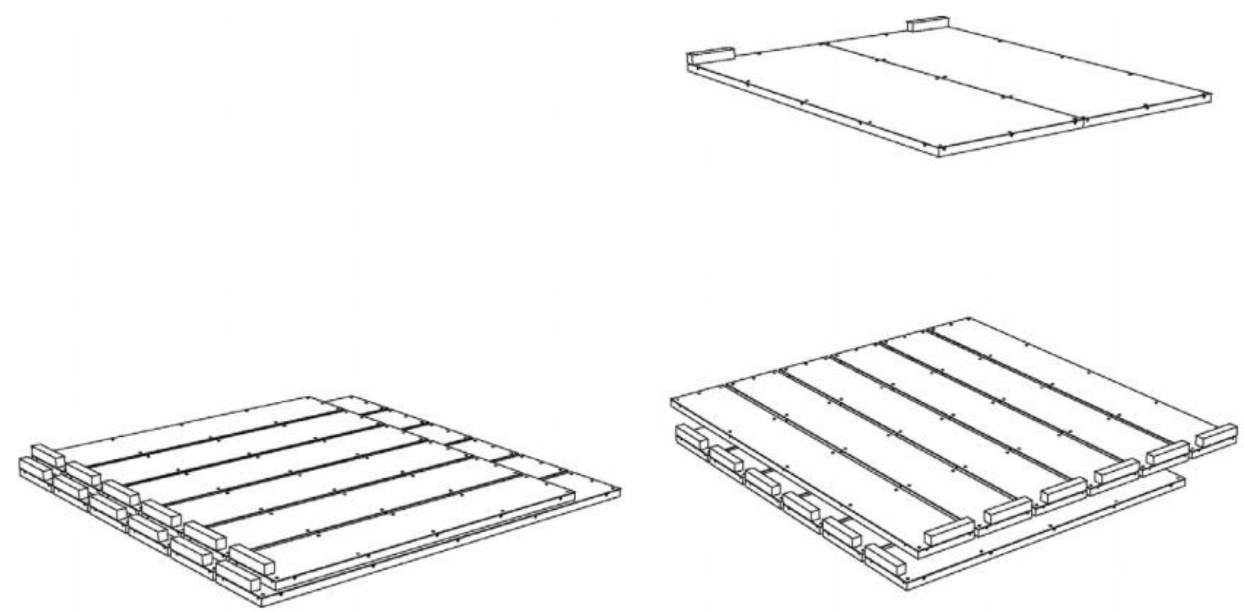


- Measured total flux: $(5.31 \pm 0.17) \times 10^{-9}\,\mu/s/cm^2$.

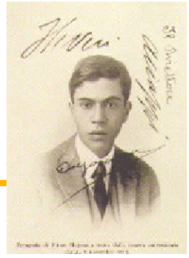
Muon Flux paper
Astropart. Phys. 93, 70 (2017)
[arXiv:1602.07742]







Low Energy Program

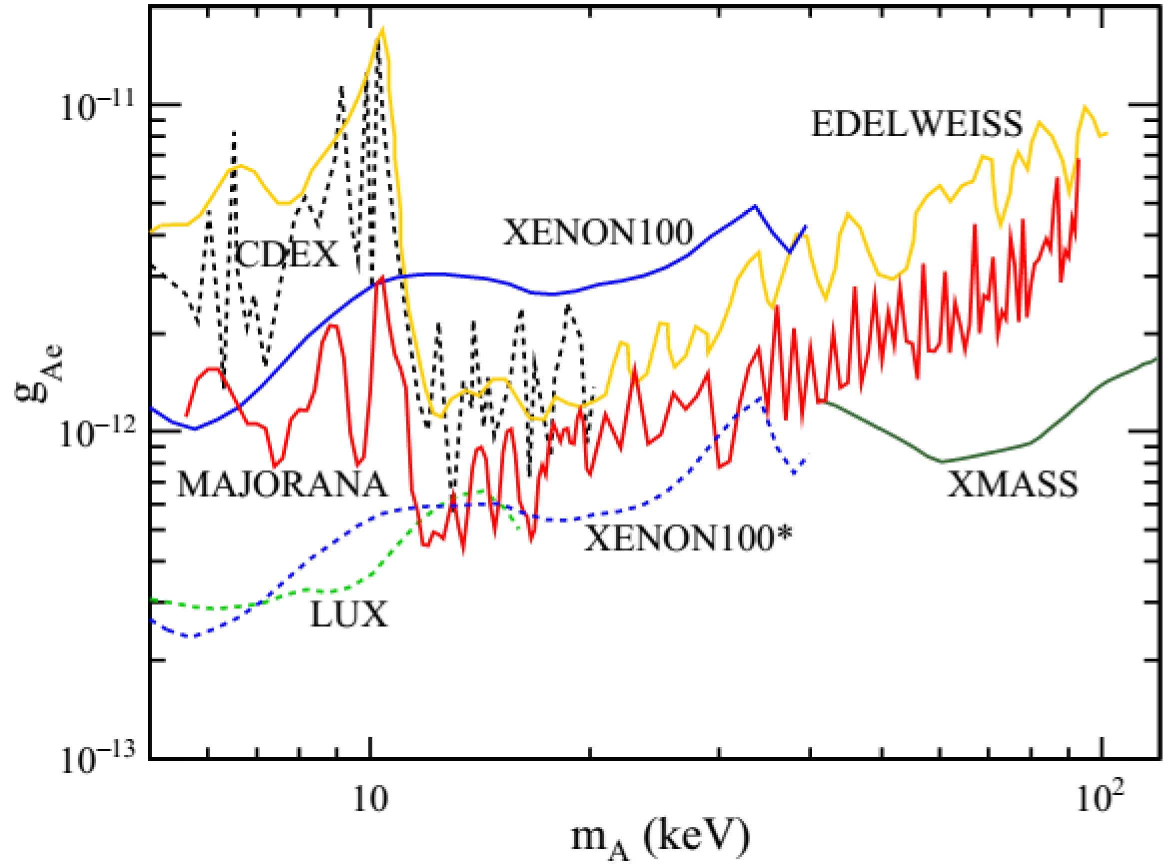


- Low backgrounds and properties of the PPC HPGe detectors, allow for low energy searches for physics beyond the standard model.

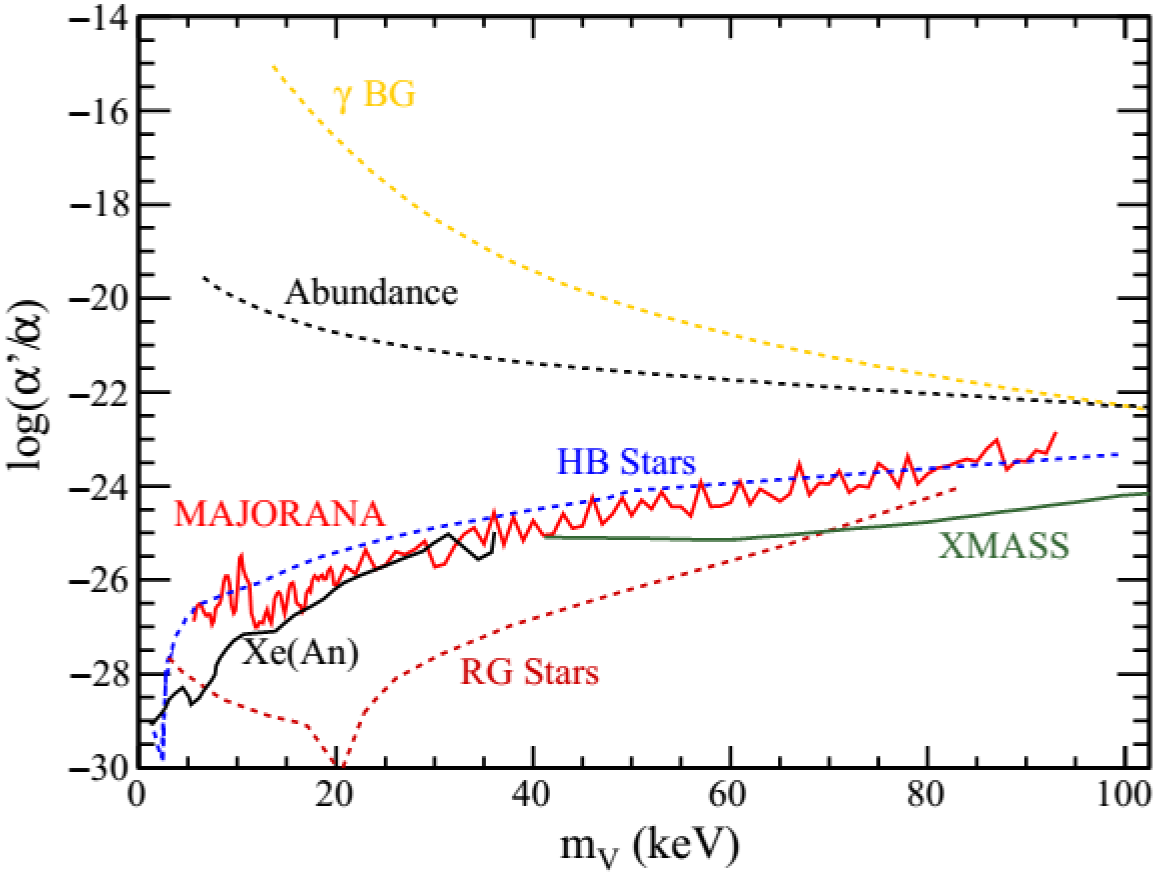
Searches beyond SM

- Pseudoscaler dark matter
- Vector dark matter
- 14.4 keV Solar axion
- Pauli Exclusion Principle
- $e^- \rightarrow \nu\bar{\nu}\nu$

Low Energy paper
Phys. Rev. Lett. **118**, 161801 (2017)
[arXiv:1612.00886]

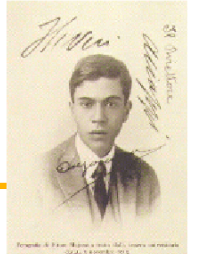


Pseudoscaler axion-like DM coupling



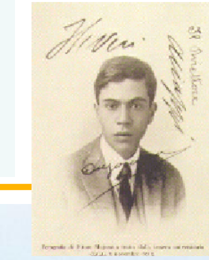
Vector particle DM coupling

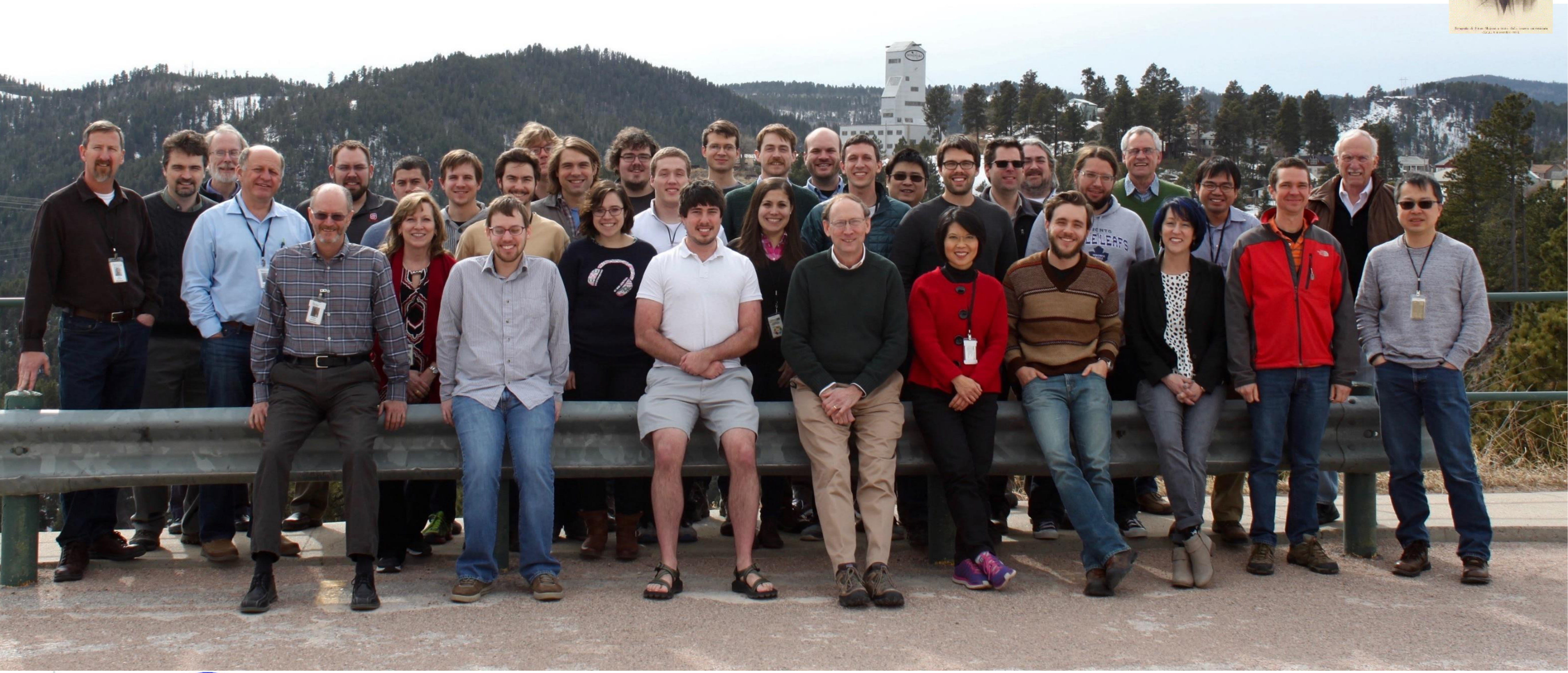
MAJORANA DEMONSTRATOR Summary



- Commissioning is complete.
  - Both modules are collecting data in the final configuration.
- The ^{76}Ge enriched point contact detectors developed by MAJORANA
  - have attained the best energy resolution (2.4 keV FWHM at 2039 keV) of any ββ-decay experiment.
  - provide excellent pulse shape discrimination reduction of backgrounds.
  - at low energies have sub-keV energy thresholds and excellent resolution allowing the DEMONSTRATOR to perform sensitive test in this region for physics beyond the standard model.
- The DEMONSTRATOR's initial backgrounds are amongst the lowest backgrounds in the ROI achieved to date (approaching to GERDA's recent best value). Attained by development and selection of ultra-low activity materials and low mass designs.
- Combining the strengths of GERDA and the MAJORANA DEMONSTRATOR, the LEGEND Collaboration is moving forward with a ton-scale 76Ge based experiment. Based on the successes to date, LEGEND should be able to reach the backgrounds (~0.1 c /(ROI t y) and energy resolution necessary for discovery level sensitivities in the inverted ordering region.

The MAJORANA COLLABORATION





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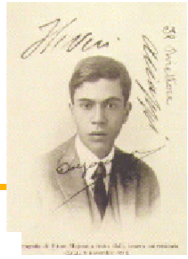
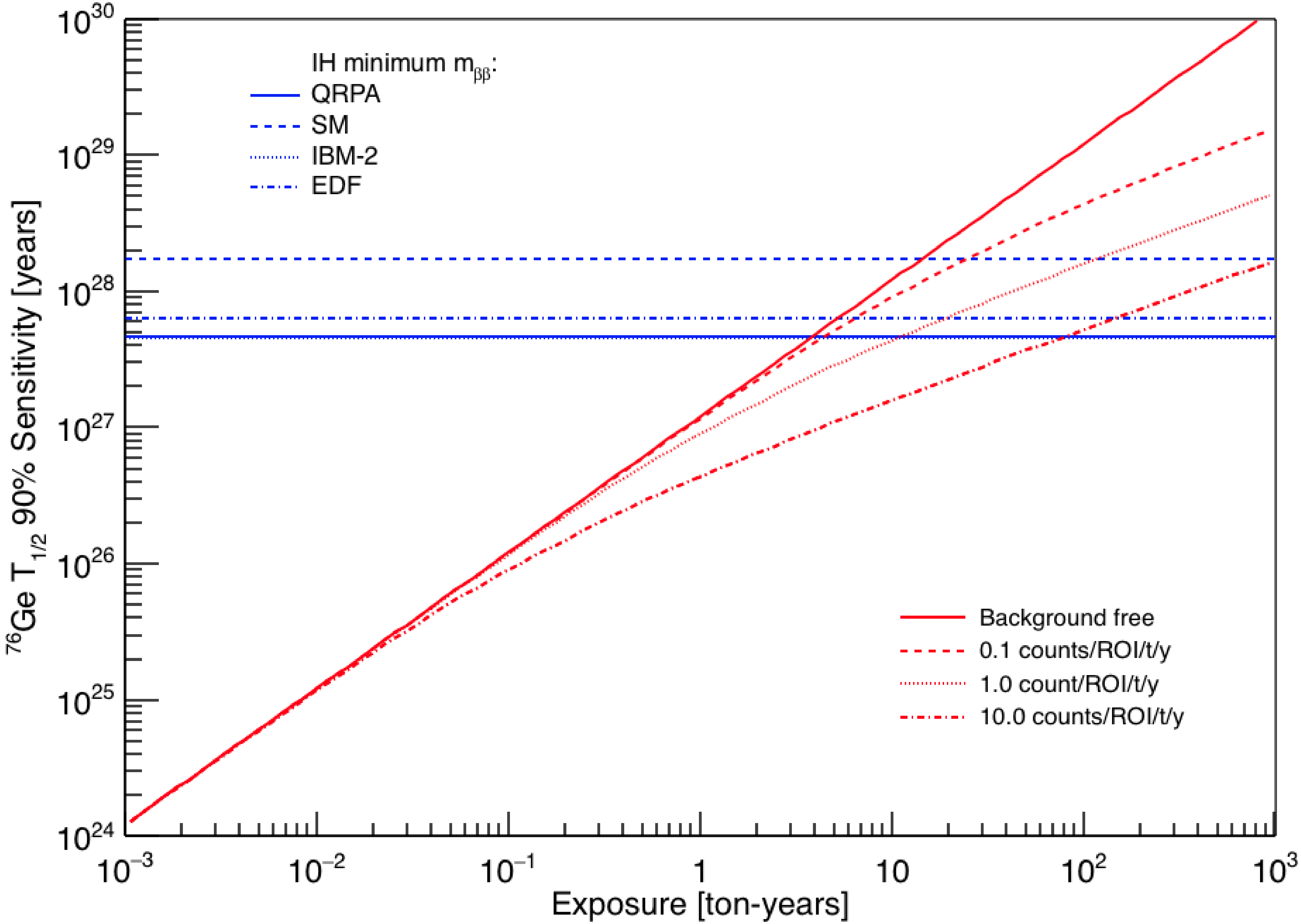
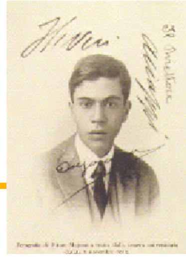
Backup Slides

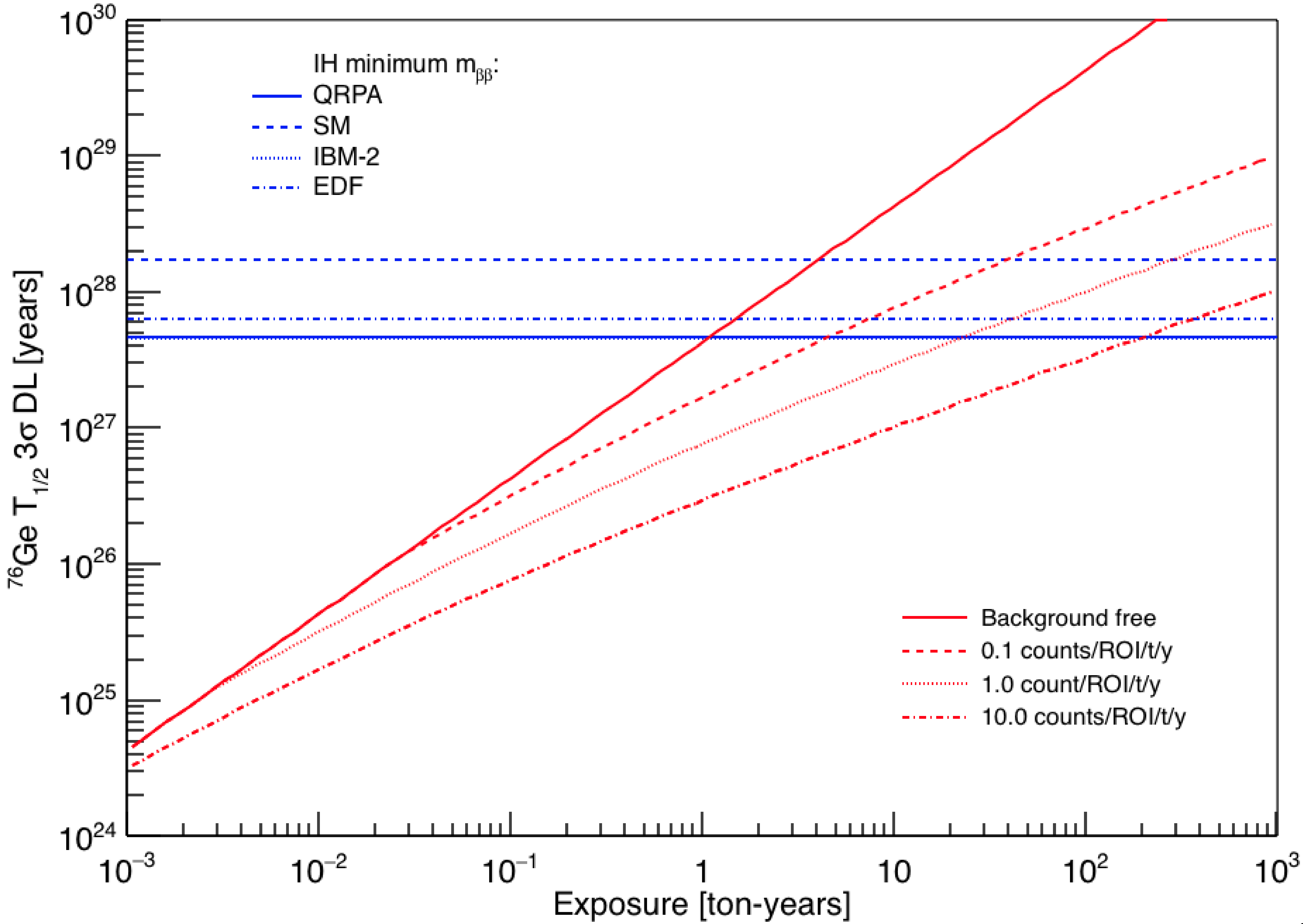
Sensitivity, Background and Exposure



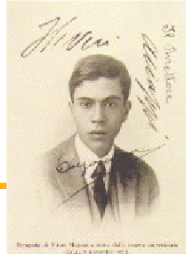


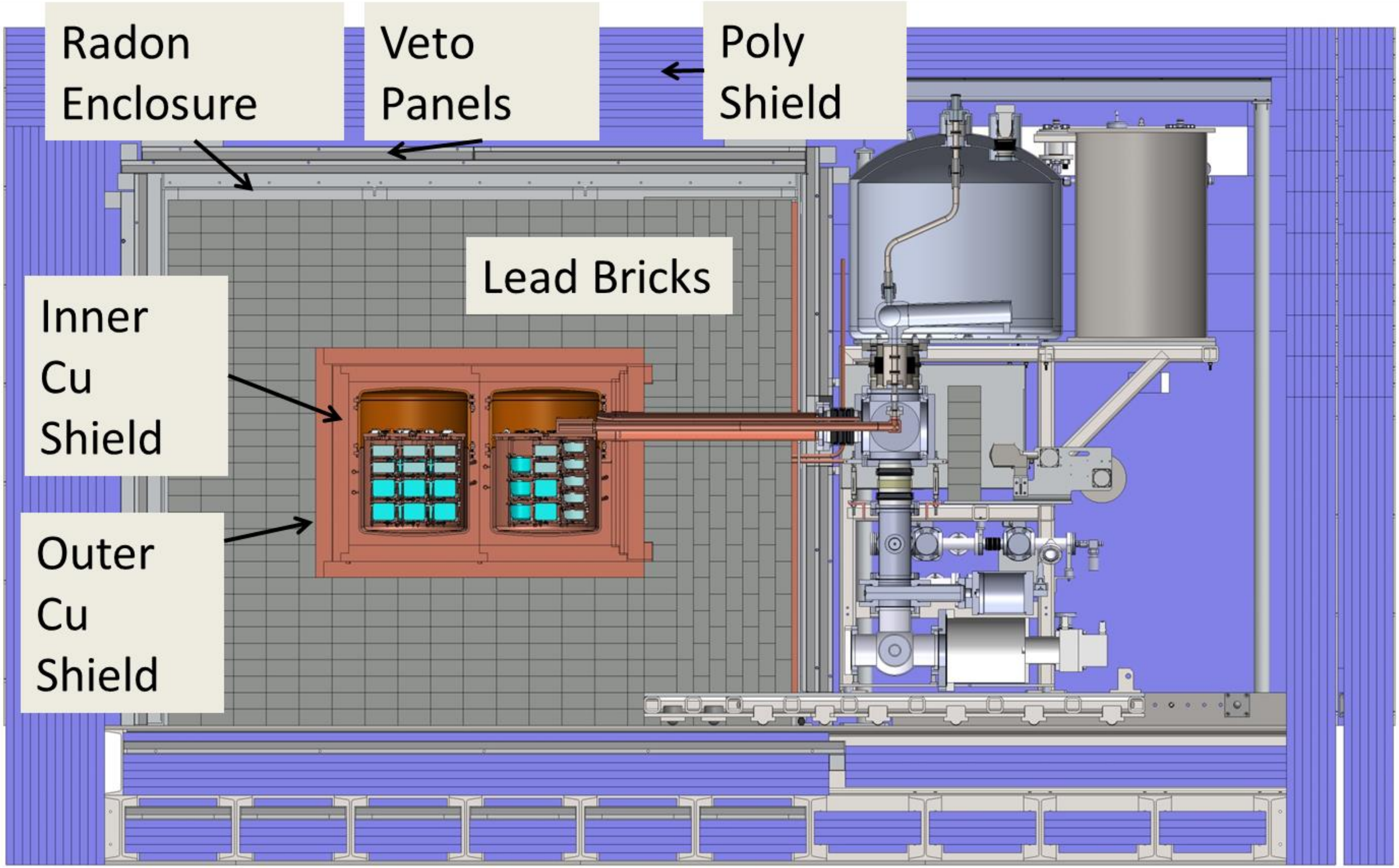
Discovery, Background and Exposure





Apparatus Overview





MAJORANA Underground Laboratory